NON-DESTRUCTIVE METHODS AND PROCESS CAPABILITY ANALYSIS TO ASSESS CONFORMANCE OF DOUGLAS FIR STANDS TO CUSTOMER QUALITY SPECIFICATIONS*

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ABSTRACT

Largest branch diameter in the breast-height region (LLBH) and acoustic velocity on lower bole were measured on trees in a 20-year-old Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) experiment comparing seven density management/fertiliser regimes. The less dense regimes tended to have larger mean branch diameter at breast height, with fertiliser increasing the mean even further. However, except for the densest regimes, the difference between a density regime and its counterpart with fertiliser was not statistically significant. The densest regime had significantly higher mean acoustic velocity than the other regimes, which were all the same except for one with very low velocity attributed to abnormal wood formed after damage by black bears. Although statistical significance may be lacking with respect to mean properties, subtle differences in their distributions may be important to timber sellers where purchasers often pay premiums for stands with higher percentages of trees that meet their process and customer needs. A statistical

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quality control procedure, process capability analysis, was used to assess the conformance of each regime to specifications for largest branch diameter at breast height and acoustic velocity. Conformance of largest branch diameter to a 35-mm maximum ranged from 84% to 100%, with fertiliser reducing conformance by 10–15%. Conformance of acoustic velocity to a 3.5 km/sec minimum ranged from 15% to 85%, with negligible difference between a thinned regime and its counterpart with fertiliser. Joint conformance ranged from 10% to 85%, with generally lower conformance associated with fertiliser. There is potential for using statistical quality control techniques to assist with timber marketing, harvest planning, and monitoring stand development.

Keywords: statistical quality control; process capability analysis; fertiliser; thinning; knot diameter; wood stiffness; acoustic velocity; nondestructive testing; wood quality.

INTRODUCTION

Rising costs and declining quality are causing forest products manufacturers to seek improved methods for assessing timber stands so they can acquire raw materials better suited to their process and customer needs. Many of them may pay a premium for stands containing trees with higher conformance to these needs. Similarly, those who manage and market timber are seeking improved assessment methods so they can monitor developing stands and determine which are best suited for specific markets. Matching quality characteristics of stands with market needs requires improved methods for measuring and linking these characteristics along the tree-to-log-to-product chain, and using procedures for assessing the degree of conformance of a stand to a set of specifications for these characteristics. In this section we discuss several wood quality characteristics and relatively simple procedures for estimating them from measurements of standing trees. This is followed by a review of a statistical quality control technique, process capability analysis (PCA), that can be used to assess the conformance of trees in a stand to a specification for one or more quality characteristics.

Important Log Characteristics and How They Can Be Assessed In Trees

Examination of log grades and sorts, product recovery studies, and discussions with log buyers indicate that the following four log characteristics predominate in log specifications.

Knot diameter

Log grades and sorts have knot diameter limits (Bowers 1997) and product recovery researchers have found that largest limb average diameter* (LLAD) (Fahey *et al.*

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* Measure the diameter of the largest knot in each lengthwise face (quadrant) and obtain the average

1991), also known as branch index (Barbour & Parry 2001), is a good predictor of product grade recovery from a log. One can hypothesise that a measurement of knot diameter on the lower stem of a tree would be correlated with the largest limb average diameter of the first log, and perhaps upper logs, within trees. One study in a 20-year-old Douglas fir spacing trial found that the diameter of the largest branch in the breast-height region of trees* is strongly correlated with both the largest limb average diameter and the largest diameter branch of the first 5-m log (Briggs 2005). These relationships can be used to translate a specification for the largest knot diameter or largest limb average diameter for logs into a simple measurement of largest branch at breast height that adds little to field time and cost.

Ring width, ring count

Researchers working with a variety of species have found that ring width is an important determinant of the flexural properties of softwood lumber (Pearson & Ross 1984; Biblis *et al.* 2004). Although the ring width effect is often the result of confounding the relatively wider rings of weak juvenile wood with the narrower rings of stronger mature wood, nevertheless restrictions on ring width occur for many grades within US softwood lumber grading rules (WWPA 2004) and in log grading rules (Bowers 1997). Mills often place a limit on “fast growth” and either pay less or will not accept logs that exceed this limit. In the Pacific Northwest, this limit is often a ring width of 0.25 inch (6.35 mm) (ring count of 4 rings/inch or 1.6 rings/cm), For some products, log purchasers prefer and pay a premium for “slow” growth. On the other hand, timber growers try to maximise growth returns on timber, and so the desires of grower and customer may be contradictory; hence, acceptable ranges are negotiated. Ring width and ring count are easily assessed on log ends and commonly assessed for the outer one-third of the radius (Bowers 1997). This is more difficult in standing trees but periodically measured plots or increment cores can be used to assess recent growth rates. One can expect growth rate on the lower stem of a tree to be a good indicator of the growth rate of the first log in the tree, since the lower stem is within that log. Forest growth models can be another alternative since annual growth rates can be estimated from changes in diameter at breast height (dbh) between projection periods.

Log diameter

Due to product line and manufacturing technology constraints, each mill has an upper and lower limit on the log diameter it can process. Within these limits, a mill

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* For Douglas fir, find the first branch whorl above breast-height and measure the diameter of the largest branch in the region from midway to the next lower whorl and midway to the next higher whorl.

may have a preferred range for which it will pay a premium. The tree diameter at breast height, combined with a taper curve to predict diameters inside bark, can be used to estimate log diameters. Since diameter at breast height is customarily measured in an inventory, measuring this property adds no new cost. Forest growth models often project the diameter at breast height of individual trees and produce log stock tables that would provide data on logs by diameter classes.

Wood stiffness

For structural lumber products and for lumber and veneer used in the manufacture of engineered wood products, wood stiffness and strength are critical properties, commonly assessed by bending tests; the terms are “modulus of elasticity (MoE)” and “modulus of rupture (MoR)” respectively. Since they are correlated, testing focuses on modulus of elasticity which can be assessed non-destructively. Non-destructive testing of lumber and veneer for modulus of elasticity is commonly used to sort these materials into stiffness and strength classes that provide designers with flexibility and reliability in product and structural design. As these applications have grown, researchers have developed techniques to relate average stiffness of products in a log to the stiffness of the log and have developed simple non-destructive methods for assessing stiffness in logs and trees. These non-destructive methods exploit the relationship between the modulus of elasticity of a material, its density, and the speed of an acoustic wave through the material (Ross *et al.* 1999; Wang *et al.* 2001, 2002, 2003, 2004). This research has led to commercial tools for non-destructive testing and sorting of logs using acoustic velocity (Carter *et al.* 2004). The success of this approach has led to more recent development of tools to assess acoustic velocity of wood in the lower bole of standing trees (Carter *et al.* 2004). Acoustic velocities of a tree and the logs it contains are correlated, providing a means by which a mill specification for stiffness can be translated into acoustic velocity for logs and then into its counterpart for standing trees.

Process Capability Analysis

Statistical quality control (SQC) is widely used in industrial manufacturing settings ranging from aircraft and automobiles to lumber size control to canned goods. One typically takes a sample of product at some stage during the manufacturing process, or of the finished product, and measures some specific property, such as the thickness of lumber, or fill level of the can. The mean and variation of the sample are typically used in two contexts. Firstly, the sample can be compared with prior samples to determine whether or not there is evidence of change. If there is, investigations would be carried out to identify and understand the causes so the process and property could be stabilised and improved. This first context involves the use of “control charts” for monitoring the process over time. Secondly, the sample can be compared with external specifications for the property to determine the degree to which it conforms. If conformance is poor, investigations would be undertaken to determine how the process could be changed to improve conformance. This context involves the use of "process capability analysis" which refers to techniques for studying capability of a process at either a single point in time or over time through repeated sampling (Montgomery 2001).

While many applications of statistical quality control can be found for forest products manufacturing processes, there is little evidence of applications in growing a stand of trees. We believe that the process of planting and intensively managing a stand of trees until harvesting is analogous to a manufacturing process starting with logs or chips to produce lumber or paper. In these situations the process converts a raw material input (seedlings, logs, chips) into a finished product output (harvested trees, lumber, paper) and managers and purchasers desire to measure the capability of the process to produce output with properties that meet specified customer needs.

Process capability is estimated by using a probability distribution with the shape, centre (mean, μ) and spread (standard deviation, σ) appropriate for the product property of interest (Montgomery 2001). Process capability can be described as the six-standard-deviation spread of the distribution of the property, expressed as "upper and lower natural tolerance limits" (UNTL, LNTL). If the property is normally distributed, process capability can be stated by noting that 0.27% of the product, or 2700 product items per million, will be outside the natural tolerance limit range for the property. Since this definition of process capability refers to the product property without reference to a specification or standard, this context is often referred to as "product characterisation".

Commonly, process capability is expressed as the percentage of product falling outside, or not conforming to, external "upper and lower specification limits (USL, LSL)" for the property. Specification limits originate from product designers, engineers, management directives, product standards, or customers and may be one- or two-sided. Assuming that the property is normally distributed, that the process is in statistical control as evidenced by control charts for the process, and that the mean is centred between the upper and lower specification limits, process capability can be expressed as a process capability ratio (C_p), the ratio of the range of the external specification limits divided by the range of the natural tolerance limits of the property (Montgomery 2001). Correct use and interpretation of C_p is dependent on the validity of the assumptions.

If the assumptions are violated or no suitable probability distribution model can be found for the property, process capability can be estimated directly by comparing the empirical frequency histogram (or empirical cumulative distribution) for the property to the interval defined by the upper and lower specification limits. Future research will be needed to discover appropriate probability distributions for tree properties that can accommodate changes resulting from silvicultural practices. An example would be a thinning that removes all trees with large diameter branches, thereby producing a truncated distribution for the residual stand. Developing the frequency histogram of a property requires the sampling of a sufficient number of trees from the stand. In constructing histograms, Montgomery (2001) suggested using between 4 and 20 bins, "choosing the number of bins approximately equal to the square root of the sample size". Thus to have six bins describing a tree property, at least 36 trees from the stand should be measured. This seems reasonable considering the typical number and size of plots for inventories and appraisals.

EXPERIMENTAL MATERIALS AND METHODS

This study examined a Stand Management Cooperative Douglas fir research installation planted in 1984. Plots were established in 1992 with three densities and each density plot had a counterpart with fertiliser applied. Trees on these plots were measured for branch diameter in the breast height region and for acoustic velocity. Objectives were (1) to assess the effect of the thinning and fertiliser regimes on branch diameter and acoustic velocity, and (2) to use process capability analysis to assess conformance of each of these regimes to specifications for branch diameter and acoustic velocity. When using process capability analysis to assess conformance to a specification, each management regime is considered to be a separate and independent process from the others. Here the intent was not to compare regimes within this experiment but to illustrate how a manager or purchaser, who typically would be examining stands grown under different regimes at different locations, would use process capability analysis to assess the conformance of a stand process to the specification.

Study Site and Experimental Design

Seven plots from the Twin Peaks Stand Management Cooperative Douglas-fir research installation in Western Washington were used (Table 1). These plots were part of a larger experiment to examine the effects of fertiliser and density management treatments on timber growth, yield, and quality. Each plot followed a management regime and was treated as a "stand" for analysis of regime effects and for process capability analysis assessment. The installation was planted at 1112 trees/ha with 2-year-old seedlings in 1984. The experimental plots were established in 1992, at which time the following series of initial density management treatments were created: a series of plots at the original or initial stems per unit area (ISPA), a series of plots at 50% of the initial stocking (ISPA/2), and a series of plots at 25% of the initial stocking (ISPA/4). Management regime identifiers and mean

TABLE 1–Description of the seven Douglas fir regimes at Twin Peaks at age 20.

Species:	Douglas fir	50-year Site Index (King 1966)	37 m
Year planted	1984	Elevation:	183 m
Stock type:	2+0	Slope:	40%
Plot establishment:	1992	Plot size:	0.2 ha

Summary after 2004 growing season

Plot No.	Regime	Stems/ha	QMD (cm)	HT40 (m)	Volume (m^3/ha)	LLBH (mm)	Acoustic velocity (km/sec)
3	ISPA_NT_NF	1038	21	21	281	19	3.7
4	ISPA_RT_NF	791	22	20	246	20	3.5
7	ISPA_RT_F	746	25	19	271	28	3.4
12	ISPA/2_MT_NF	504	26	19	203	27	3.5
8	ISPA/2_MT_F	479	28	19	228	29	3.5
1	ISPA/4_NT_NF	208	31	18	107	28	3.2
9	ISPA/4_NT_F	247	30	18	132	32	3.4

ISPA = initial stems per unit area
NF = no fertiliser; F = with fertiliser
NT = no subsequent thinning
MT = “minimal” thinning; thin at relative density (RD) 55 to RD 35
RT = “repeated” thinning; thin at RD 55 to RD 35, RD 55 to RD 40, RD 60 to RD 40
QMD = quadratic mean diameter
HT40 = mean height of 40 largest-diameter trees
LLBH = largest branch diameter at breast-height

statistics after the 2004 growing season (age 20) are listed in Table 1 on a subset of seven of these plots that formed the basis for a density management/fertiliser experiment. One initial density plot was a control that received no further treatments. Two initial density and two half initial density plots followed different thinning regimes based on relative stand density (Curtis 1982) and each of these had a counterpart plot receiving fertiliser. Finally, a 25% initial density plot that received no thinning and a counterpart with fertiliser completed the seven-regime experiment. Application of urea at a rate of 224 kg N/ha occurred at study establishment and every 4 years after that. At the time of this study, none of the regimes that included subsequent thinning had reached their relative density trigger; hence, the only density effect present was that imposed by the initial respacing. Each treatment plot consisted of a 0.2-ha measurement sample plot surrounded on all sides by a 9.3-m buffer strip.

Data Collection

The plots were measured every fourth year after establishment, most recently after the 2004 growing season. Diameter at breast height was measured on all trees in the measurement sample plot. Total height and branch data (branch count and diameters in the breast-height region described in section on *Knot diameter)* were measured on a 42-tree sample, which included the smallest tree, the largest tree, and 40 trees distributed across the breast-height diameter range with roughly two-thirds greater than the quadratic mean diameter and one-third smaller. Quadratic mean diameter, basal area, and volume were calculated at plot level for each measurement. The diameter of the largest breast-height branch was extracted from the branch data, and average height of the 40 largest-diameter trees per acre (HT40) was calculated for each plot. In the summer of 2005, acoustic velocity was measured in a 40-tree sample on each plot (Carter *et al.* 2005). Measurements were taken from approximately 30 to 140 cm above the ground and, depending on tree size, acoustic velocity was obtained from two or three locations around the circumference at this height and averaged to get mean velocity for each tree. A sub-sample of 10 of these trees was climbed with a ladder to the top of a 5-m log. The largest-diameter branch in each lengthwise quadrant was measured in order to calculate the average diameter of the largest branch for the log. These data were combined with those collected on these same trees during the preceding winter for the diameter of the largest breast-height branch.

Statistical Analysis

Analysis of variance (ANOVA) was used to determine the significance ($\alpha = 0.05$) of the effects of the regimes on diameter of the largest breast-height branch and acoustic velocity. Tukey's Studentized Range test was used to compare between regimes. Regression analysis was performed to relate diameter of the largest breast-height branch of trees to the average diameter of the largest limb of the 5-m butt log they contain.

In performing process capability analysis assessment of each regime, we followed procedures customary in statistical quality control texts (Grant & Leavenworth 1988; Montgomery 2001) which start by organising the data into frequency histograms. Organising data into histograms has a long history in statistical quality control that reflects ease of data collection, organisation, and visualisation by operational personnel. Although one could use the empirical data distributions instead, we have chosen to follow the traditional histogram approach that a manager would find in consulting one of these texts.

RESULTS AND DISCUSSION

Effect of Regimes on Largest Diameter Breast-height Branch and Acoustic Velocity

At establishment the base of the live crown was below breast height; hence, one can hypothesise that the initial thinning slowed crown recession and promoted greater breast-height branch diameter growth. One would also expect greater growth and therefore larger breast-height branch diameter with decreased stand density. Finally, one can also hypothesise that fertiliser would probably produce additional branch diameter growth. These trends are apparent in Table 1 and Fig. 1, and ANOVA revealed significant differences between the regimes. Specifically, the fully stocked regimes without fertiliser and without thinning (ISPA_NT_NF) and following repeated thinning (ISPA_RT_NF) had significantly smaller breast-height branch diameters, 19 mm and 20 mm respectively, than the other regimes. One would expect denser regimes to achieve intense competition more quickly than less dense regimes. More intense competition in dense stands would lead to slower growth of breast-height branch diameter, more rapid crown recession, and earlier branch death which collectively result in smaller breast-height branch diameters in denser regimes. Fertiliser significantly increased largest breast-height branch diameters of the fully stocked regime with repeated thinning and fertiliser (ISPA_RT_F) over its counterpart without fertiliser, 28 mm as against 20 mm, but did not produce a significant increase in the regimes with 50% stocking (ISPA/2) 27 to 29 mm and 25% stocking (ISPA/4) 27 to 32 mm. Among these less densely planted regimes, only the two extremes 50% stocking with minimal thinning and no fertiliser (ISPA/2_MT_NF) 27 mm, and 25% stocking with no thinning and fertiliser (ISPA/4_NT_F) 32 mm, were significantly different. Currently, the live crown base in all regimes has receded above breast height and so these relationships

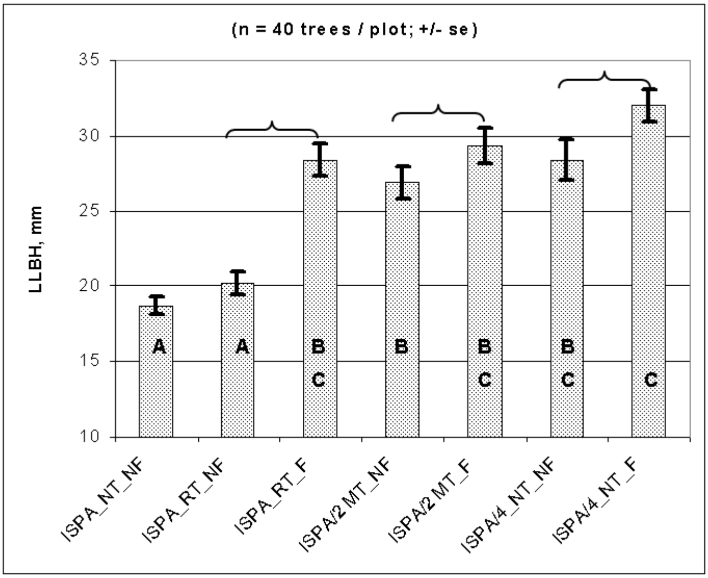

FIG. 1–Treatment regime effects on largest branch diameter at breast-height at Twin Peaks.

are unlikely to change in the future, with the possible exception that mortality, thinning, or self-pruning may alter the average largest breast-height branch diameter of the residual stand.

Reduced wood density and increased microfibril angle reduce wood modulus of elasticity (Biblis *et al.* 2004; Cave & Walker 1994; Deresse *et al.* 2003; Megraw *et al.* 1999). Others have shown that fertiliser application reduces wood density in Douglas fir (Erickson & Harrison 1974; Megraw & Munk 1974; Bodner 1984) and increases microfibril angle (Erickson & Arima 1974). One can hypothesise that fertiliser reduces stiffness; hence, regimes with fertiliser would be expected to have lower acoustic velocities than those without. The effects of thinning on wood density and microfibril angle are mixed (Briggs & Smith 1986) as the outcome depends in part on the component of the stand remaining after thinning as well as how those trees subsequently respond. Both higher (Carter *et al.* 2005) and lower (Wang *et al.* 2001) acoustic velocity have been reported for thinned compared to unthinned stands. Thus it is more difficult to express a hypothesis for the effect of thinning on acoustic velocity.

The effects of regimes on acoustic velocity are shown in Fig. 2. The fully stocked control without thinning or fertiliser (ISPA_NT_NF) had significantly higher acoustic velocity, 3.7 km/sec, than the other regimes, 3.2 to 3.5 km/sec. This may reflect the presence of slower-growing, smaller-diameter trees in this dense stand as compared to the regimes that provided more growing space and nutrients. Carter

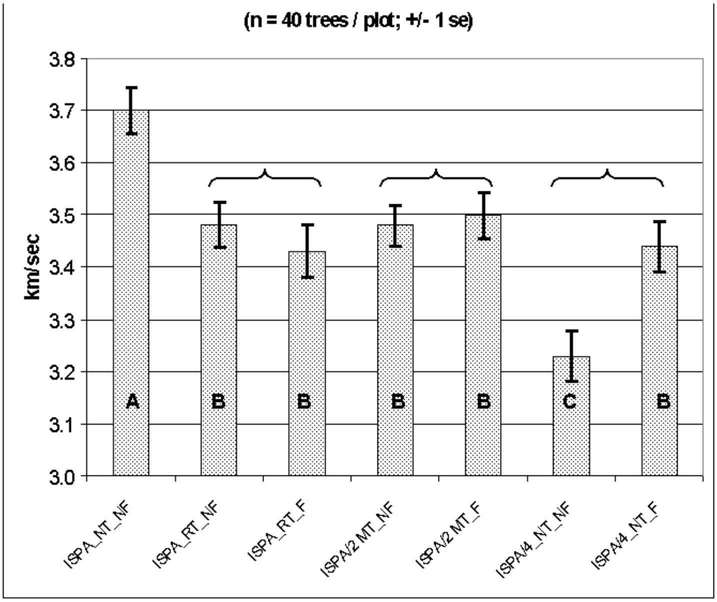

FIG. 2–Treatment regime effects on acoustic velocity at Twin Peaks.

et al. (2005) found a weak negative relationship between acoustic velocity and breast-height diameter of trees in a 49-year-old Douglas fir stand indicative of an effect of slow *versus* fast growth. The 25% stocked regime without thinning or fertiliser (ISPA/4_NT_NF) had significantly lower acoustic velocity, 3.2 km/sec, than the others. Inspection of plot records revealed that half of the trees in this regime had at least 30% of the lower bole damaged by black bears (*Ursus americanus* Pallas 1780) which strip bark to feed on the cambium. Acoustic velocity was measured in intact strips between the damaged areas but we believe that the trees were creating wound wood in response to the damage. Wound wood is anatomically different from normal wood (Kozlowski & Pallardy 1997) which may explain the amomalous results. With this exception, it appears that there is no difference among the regimes with and without fertiliser. As these regimes continue to develop in the future, differences in acoustic velocity may appear.

In general, the level of acoustic velocity (of the order of 3.5 km/sec) in these 20-year-old regimes is much lower than the 4.25 to 4.40 km/sec found in 49-year-old unthinned and thinned Douglas fir (Carter *et al.* 2005). Tree acoustic velocity is measured in the outer wood of the stem, and outer wood of 49-year-old trees is dense stiff mature wood, whereas outer wood of the 20-year-old trees is in transition from low-density low-stiffness juvenile to mature wood (DiLucca 1989; Fahey *et al.* 1991; Middleton & Munro 1989). Other possible factors that could be involved include genetic and site differences.

Conformance of a Regime to a Specification for Largest Diameter Breast-height Branch and Acoustic Velocity

Although these treatment regime effects are important, timber and log purchasers would be more interested in determining how much of each conforms to a branch diameter specification. The relationship between largest diameter breast-height branch and largest limb average diameter of the 5-m butt log for the Twin Peaks regimes is given in Fig. 3. This relationship is highly significant and explains a similar amount of variation (58%) to that found previously in a 20-year-old Douglas fir spacing trial (Briggs 2005). This equation can be used to translate a log specification for largest limb average diameter into an equivalent measure of largest diameter breast-height branch on the tree. For example, if a log purchaser has an specification that largest limb average diameter cannot exceed 35 mm, this translates into a 34.5 mm largest diameter breast-height branch equivalent, which will be rounded to 35 mm in the discussion that follows.

Given the 35-mm largest diameter breast-height branch, process capability analysis can be used to examine the frequency distributions for conformance by each of the regimes. In the fully stocked regime with repeated thinning and fertiliser (ISPA_RT_F) 86% of the trees conformed (Fig. 4). Conformance for all of the

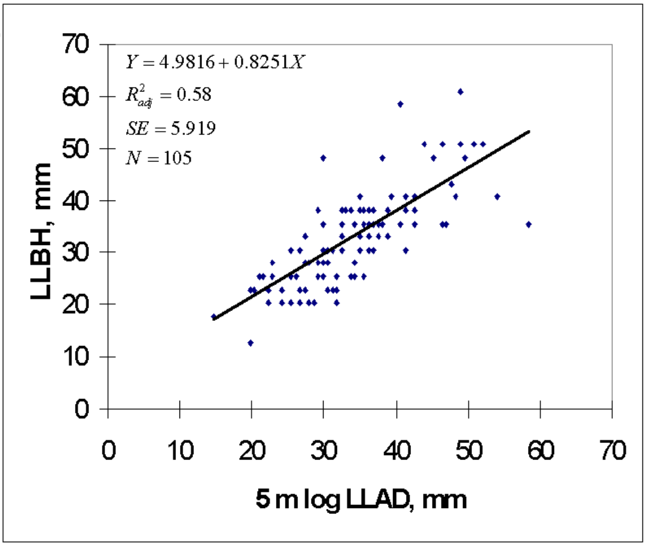

FIG. 3–Relationship between the largest branch diameter at breast-height and the largest limb average diameter of the 5-m butt log of trees at Twin Peaks.

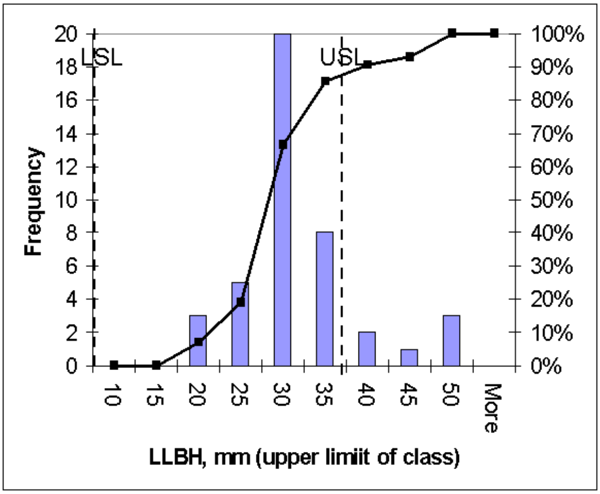

FIG. 4–Frequency of largest branch diameter at breast-height in the fully stocked regime with repeated thinning and fertiliser and conformance to a 35-mm upper specification limit.

regimes is summarised in Fig. 5; this ranges from 100% in the control to 64% in the 25% stocked regime with fertiliser and no thinning (ISPA/4_NT_F). Note that each regime with fertiliser has conformance levels of the order of 10 to 15% lower than its counterpart without fertiliser. Thus, while some of the regimes may not be significantly different in terms of mean largest diameter breast-height branch,

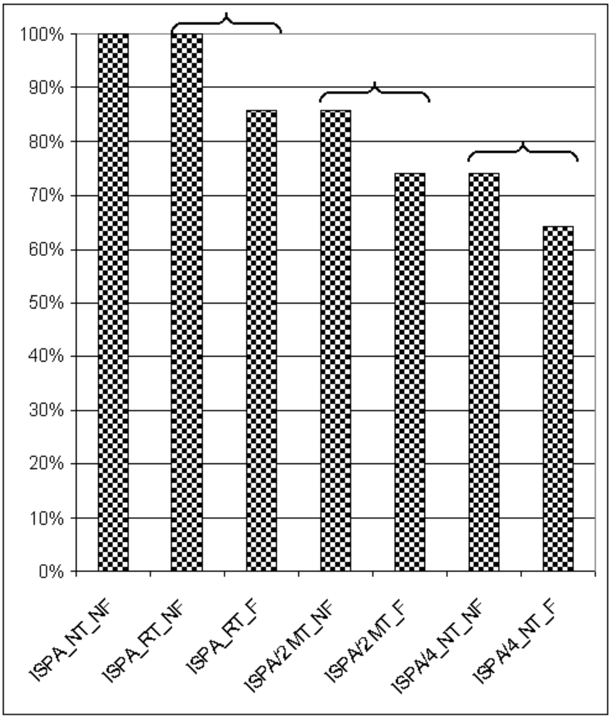

FIG. 5–Conformance of seven regimes to a 35-mm upper specification limit on largest branch diameter at breast-height.

potentially important differences to sellers and purchasers may be present, particularly if there are price premiums for conforming material.

As with branch diameter, timber and log purchasers would be interested in determining conformance to an acoustic velocity specification. To illustrate, suppose a purchaser specifies that acoustic velocity must exceed 3.5 km/sec. Conformance for the fully stocked regime with repeated thinning and fertiliser (ISPA_RT_F) where 47.5% of the trees conform is illustrated in Fig. 6. Conformance for all regimes, which ranges from 15% in the bear-damaged 25% stocked regime with no thinning or fertiliser (ISPA/4_NT_NF) to 85% in the fully stocked regime with no thinning or fertiliser (ISPA_NT_NF), is illustrated in Fig. 7.

Typically, simultaneous conformance to all components of a specification would be required. Joint conformance to the specifications for largest diameter branch at breast height and acoustic velocity is summarised in Fig.8. Joint conformance ranges from 10% to 85% and, with the exception of the bear-damaged regime, it appears that the plots with fertiliser have somewhat lower joint conformance than their counterparts without fertiliser.

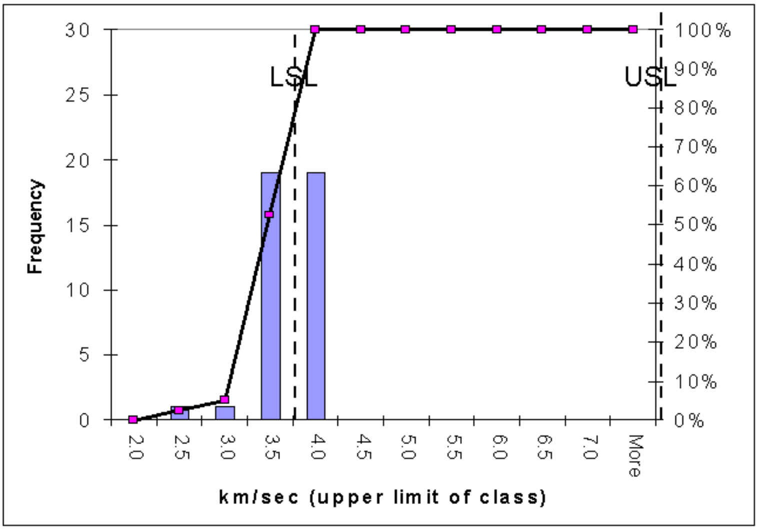

FIG. 6–Frequency of acoustic velocity in the fully stocked regime with repeated thinning and fertiliser and conformance to a 3.5-km/sec lower specification limit.

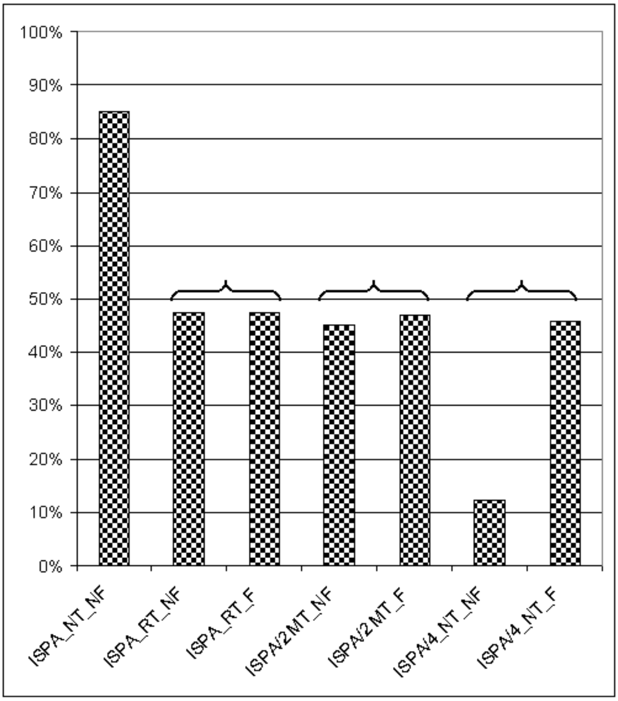

FIG. 7–Conformance of seven regimes to a 3.5-km/sec lower specification limit on acoustic velocity.

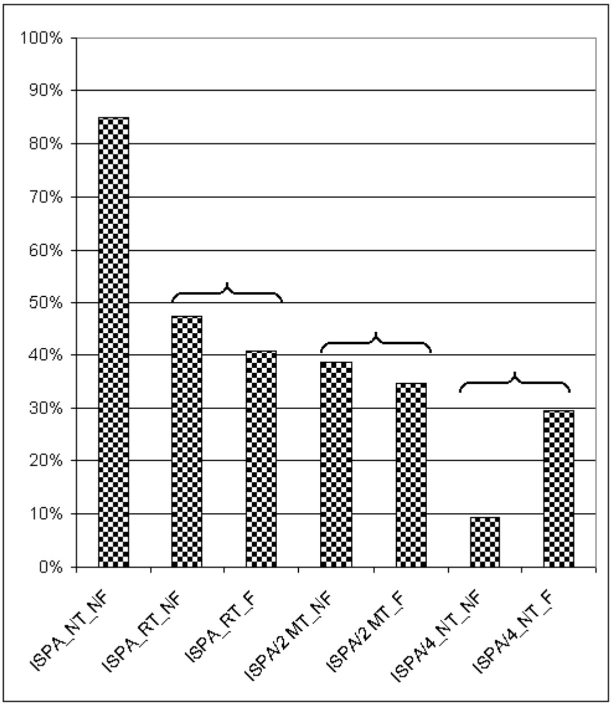

FIG. 8–Joint conformance of seven regimes to the largest branch diameter at breast-height and acoustic velocity specifications.

MANAGEMENT IMPLICATIONS

Timber Marketing and Harvest Planning

Quantifying various timber characteristics based on customer specifications and stratifying a stand according to joint conformance provides a flexible method for presenting information to customers. Furthermore, it provides sellers with improved insight as to which customers are most likely to be interested in a stand so that the marketing of it can be more targeted. Joint conformance information on the suite of stands scheduled for harvesting can be used to develop customised tree or log sort tables that can be integrated into decision-support systems and models such as harvest scheduling and allocation. The integration of these one-time process capability analyses of marketable stands with harvest planning and allocation would add value to both sellers and purchasers. The former benefit by having better information for targeted marketing, while the latter have more assurance of purchasing stands that are well suited to their needs. Furthermore, future research and development may provide methods for measurment of wood quality characteristics by harvesting equipment, and for incorporating this information in adaptive control of log bucking to meet plans and orders (Murphy *et al.* 2004).

Silviculture Planning

Use of statistical quality control techniques has been discussed in the context of adaptive management of renewable resources where changes over time after a manipulation can be predicted from hypothesised development processes and subsequently monitored to test the accuracy of the predictions (Walters 2002; Oliver *et al.* 1992). The approach presented in this paper offers an opportunity to apply adaptive management to specific tree properties. Considering the fact that the Twin Peaks regimes are only 20 years old, a silviculturist could examine the conformance data, perhaps stratified further by breast-height diameter, to assess potential ways that joint conformance could be improved. How would conformance change if a certain component of the stand is removed? If this component is removed, what is the conformance of the residual stand? How will the properties of the residual trees develop in the future, and will conformance improve or worsen? What should be done with stands that are unlikely to develop adequate conformance? Issues such as these imply the use of periodic samples to monitor properties and joint conformance to a set of target specifications. Monitoring would also permit quantification and improved understanding of how treatment of a stand affects conformance. The concept of monitoring a process over time is embodied in the control chart approach of statistical quality control. Adoption of these methods for assessing and planning silvicultural actions should be investigated further. Since silviculturists commonly use growth and yield models to project the probable outcome of applying treatments, additional research is needed to incorporate predictions of knots, stiffness, and other properties in these models, so they can provide feedback on conformance and allow silvicultural planners to use the adaptive management approach.

CONCLUSION

This study examined the effect of seven density management-fertiliser regimes in 20-year-old Douglas fir on knot diameter, measured as the diameter of the largest branch in the breast-height region, and on wood stiffness nondestructively assessed using acoustic velocity on the lower stem. There was a tendency for the less dense regimes to have larger branch diameter at breast height, with the addition of fertiliser increasing this further. However, with the exception of the regimes with dense initial stems per unit area, the difference between a density regime with no fertiliser and its counterpart with fertiliser was not statistically significant. For acoustic velocity, the control regime had significantly higher velocity than other regimes. The other regimes were all the same except for one with very low velocity attributed to abnormal wood formed after damage by black bears.

The study also used a statistical quality control procedure, process capability analysis, to assess the conformance of trees within regimes to purchaser specifications for largest diameter branch at breast height and for acoustic velocity, both separately and jointly. Although some regimes were not significantly different, potentially important differences in conformance to purchaser specifications were found. Conformance of breast-height branch diameter to a 35-mm maximum ranged from 84% to 100%, with fertiliser reducing conformance by 10–15%. Conformance of acoustic velocity to a 3.5-km/sec minimum ranged from 15% to 85%, with negligible difference between a thinned regime and its counterpart with fertiliser. Joint conformance ranged from 10% to 85%, with generally lower conformance associated with fertiliser.

The process capability analysis approach permits one to redefine specification limits and restate joint conformance as customer needs and market conditions change, and can lead to more flexible and sophisticated definition of timber sorts useful for marketing, harvest planning, and assessing conformance of stands to target specifications as they develop. The approach can be easily expanded to include other properties, such as diameter and ring count, important to purchaser log specifications and which can be translated into simple easy-to-measure equivalents for standing trees.

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